Cosmic Rays at Mesoscopic Scales

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Overarching Questions

- How do cosmic rays spread from their sources through space and time?
- How do cosmic rays exchange energy & momentum with the ambient medium?
- What are the observational signatures of these processes?

Plan of This Talk

- Brief review of transport theories
  - Self confinement, extrinsic confinement, propagation 2.0
- The bottleneck effect & its manifestations
  - A signature of self confinement?
- Energy exchange between cosmic rays & large scale turbulence
  - A distributed source of energization?
- Effects of cosmic ray injection on the structure of the Galactic disk
  - Thermal phases
  - Scale height of gas layer
  - Orientation of magnetic field

Cosmic Ray Transport

- ***Streaming:*** Cosmic rays couple to thermal gas by scattering from MHD waves they excite by streaming down their pressure gradient.
  - Waves propagate down-gradient.
  - Scattering rate adjusts to maintain marginal stability.

Stream relative to the gas at

$$\mathbf{v_{Ai}} \equiv \frac{\mathbf{B}}{(4\pi\rho_i)^{1/2}}$$

Heat the gas at the rate

$$H = \mathbf{v_{Ai}} \cdot \nabla P_c$$

"Continuity" condition

$$P_c \propto \rho_i^{2/3}$$

along each magnetic flux tube.

- ***Diffusion:*** Cosmic rays scatter from extrinsic turbulence

Diffuse through the gas with diffusivity κ.

- ***Advection:*** Limit of small diffusivity.
- Behave like a relativistic gas

$$P_c \propto \rho_i^{4/3}$$

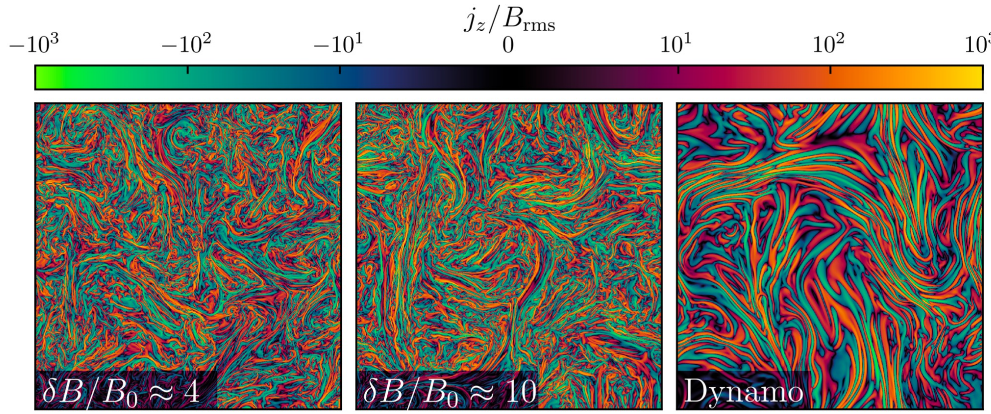
In both models, cosmic rays do work on the gas through their pressure gradient.

Only the streaming model heats the gas & predicts the diffusivity.

Both models require presence of MHD fluctuations on cosmic ray gyroradius scales.

Propagation 2.0

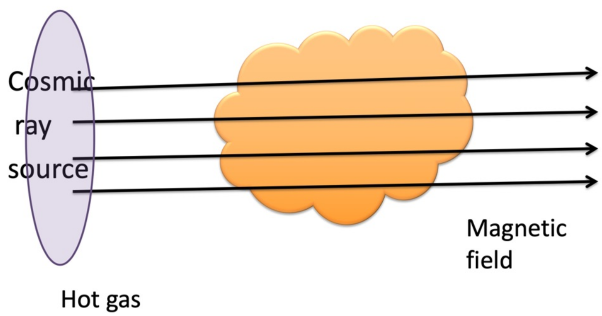
- Self confinement & extrinsic confinement share a common description of microscopic scattering mechanism:
  - Uniform background field with gyroscale, uncorrelated, MHD fluctuations.
  - Picture must be untenable above some energy.
  - May be adequate for the GeV "worker bee" cosmic rays.



Kempski 2022

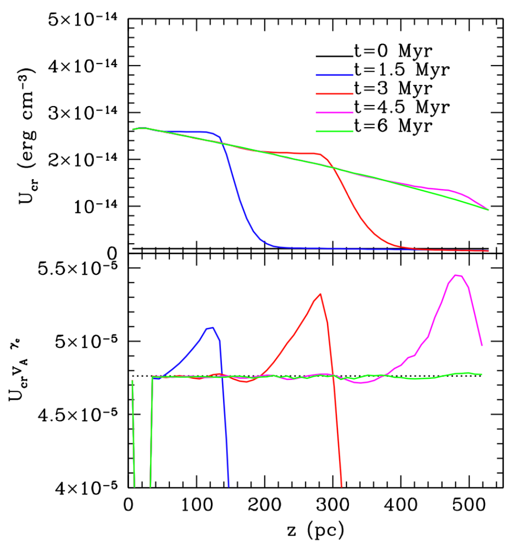
Ongoing studies based on orbit tracing of test particles in self consistent models of MHD turbulence.

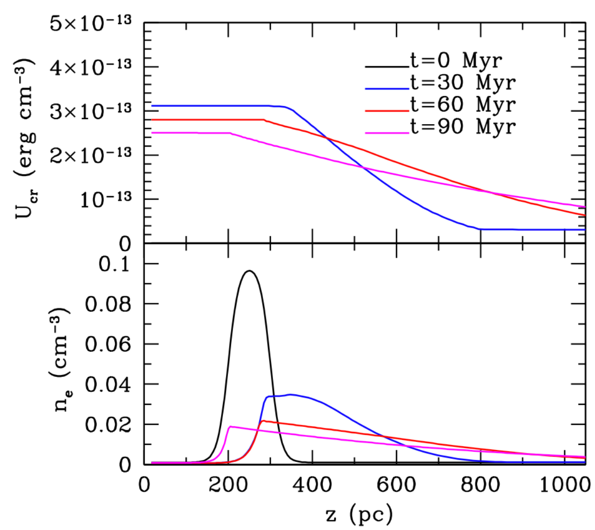
The Bottleneck Effect: (Bustard, Oh, Ruszkowski, Wiener)

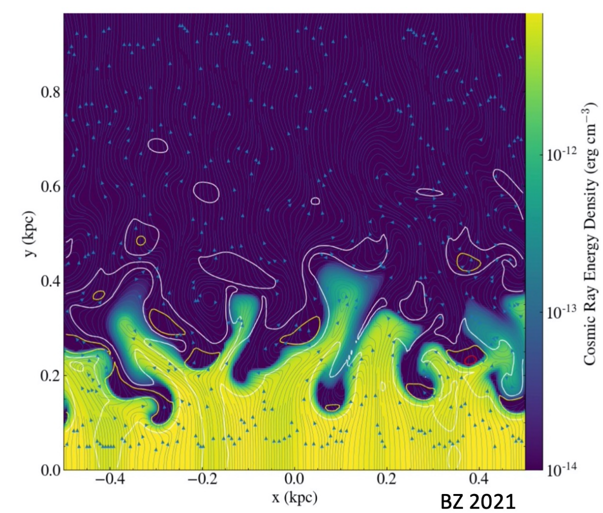


Can occur whenever cosmic ray pressure gradient & plasma density gradient are anti-aligned.

- Down-gradient side of cloud is eroded by heating.
- Pressure pulse imparts momentum.
- Between source & v_{Amin}, cosmic rays & gas are decoupled.

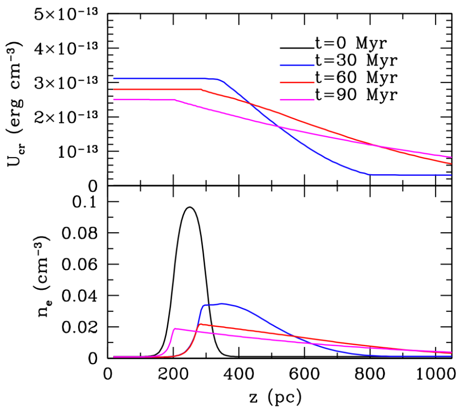






BZ 2021

The Cloud – Intercloud Transition Layer *(Zhu, EZ, Gnedin submitted to ApJ.; on arXiv tonight)*



Resolve the transition layers on the far side of the cloud.

$$\rho v = \text{constant},$$

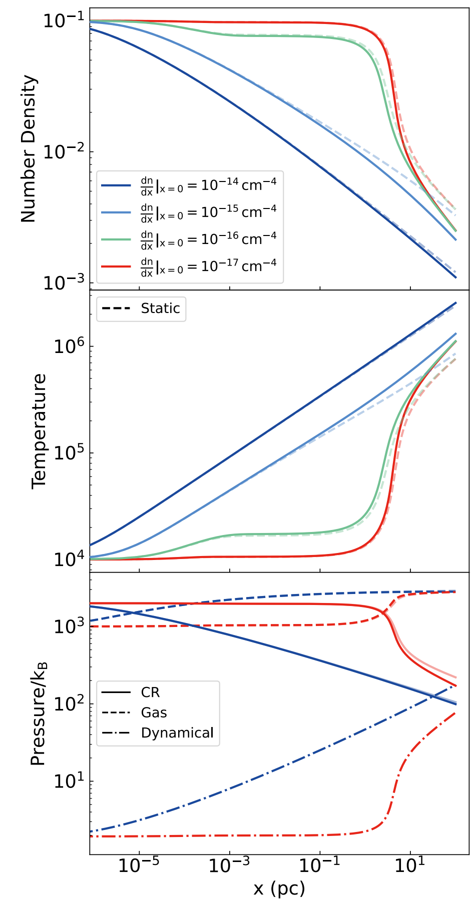
$$\rho v^2 + P_g + P_c = \text{constant},$$

$$P_c/\rho^{\gamma_c/2} = \text{constant}.$$

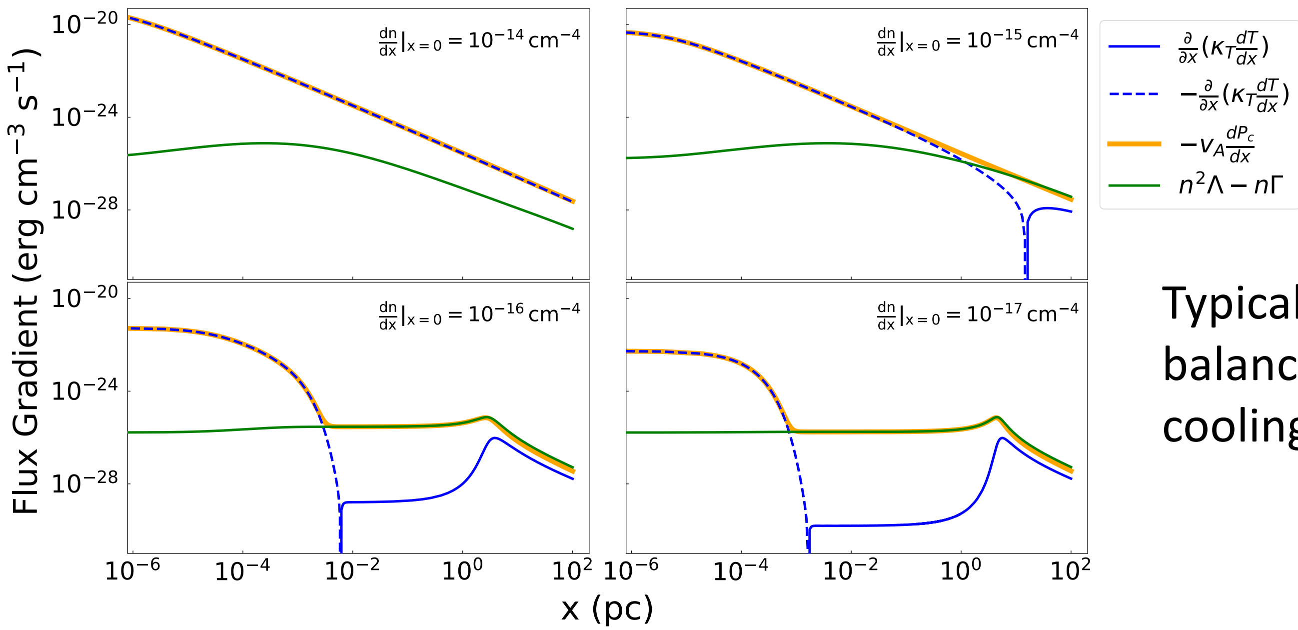
$$\frac{\partial}{\partial x}\left[(E_g + P_g)v - \kappa_T \frac{\partial T}{\partial x}\right] = -\rho\mathcal{L} - (v + v_A)\frac{\partial P_c}{\partial x},$$

All 4 models have $P_{cr}=2P_g$ at the boundary of the cloud.

Distinguished only by their initial density gradient, which sets the cosmic ray heating rate.



Relative Importance of Heating & Cooling Terms in Energy Eqn.

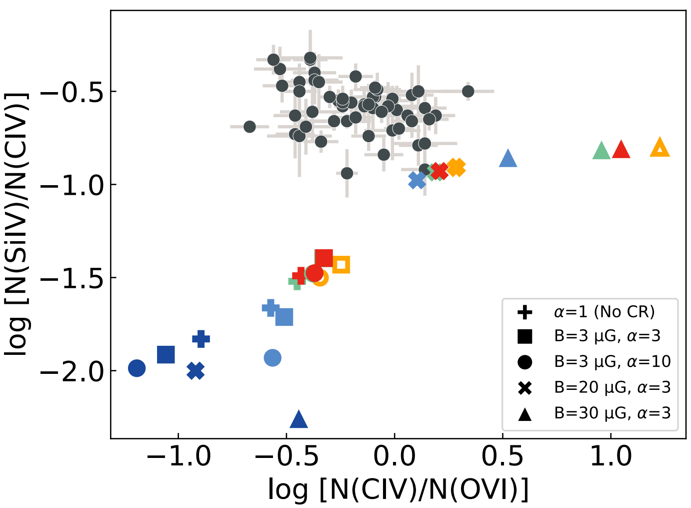


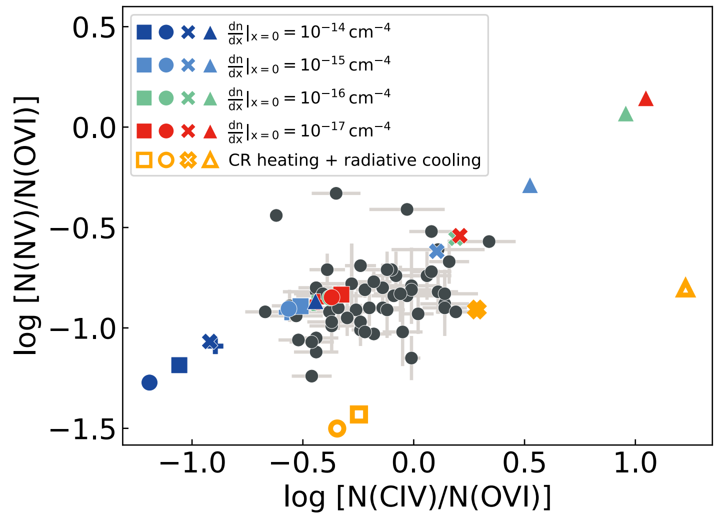
Typically, cosmic ray heating is balanced by conductive & radiative cooling.

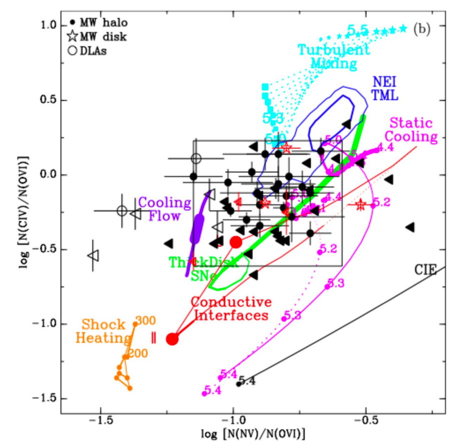
Observational Tests *(Data from Wakker et a. 2012)*

Column density ratios of transition temperature (104 < T < 106 K) ions can probe the temperature profiles of thin layers In the Milky Way halo & circumgalactic medium.

Column densities are derived from absorption line spectra of extragalactic sources.







Models which fit the data support self confinement theory, but we make no claims for their uniqueness.

Next Up

- Linear stability analysis in 1D
- Time dependent solutions

What sets the initial density gradient? (the first two items, marked with a brace)

- Corrugational (2D or 3D) instability

Self Confinement vs Extrinsic Confinement

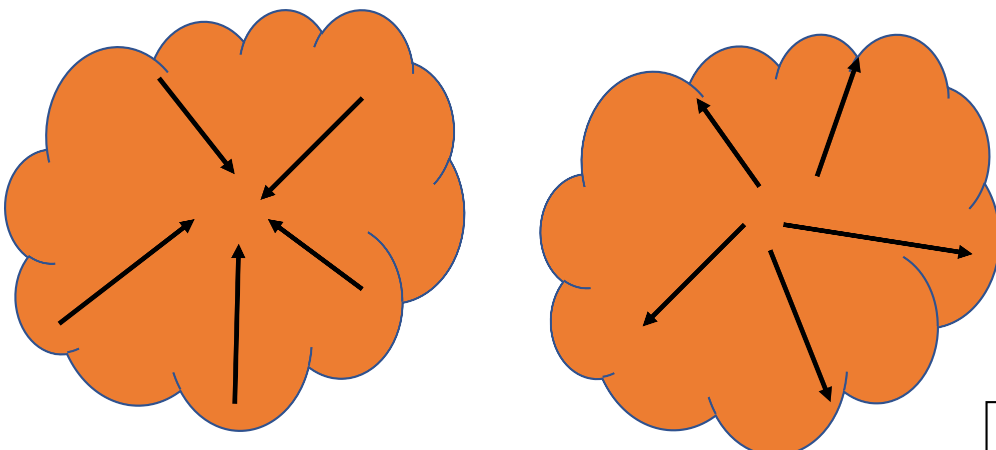
- Self confinement:
  - Bottlenecks predict intermittent cosmic ray-gas coupling, based on alignment of thermal gas and cosmic ray pressure gradients.
  - P_c/P_g can be large in clouds that create bottlenecks.
  - Sharp gradients in gas density can be sites of extreme heating.
- Extrinsic confinement:
  - Diffusivity is a cosmic ray independent property, determined by properties of turbulence.
  - Uniform diffusivity predicts cosmic rays follow the gas.
  - Gas & cosmic rays are coupled only above scales defined by a "cosmic ray Reynolds number".

Diffusive Cosmic Ray Propagation in Large Scale Turbulence *(Habegger, Yuen, Ho, EZ 2024)*

Goes back to Ptuskin 1986,

recently revived by Bustard & Oh,

Commercon.



Compression Expansion
More scatterings during compression than expansion: ``second order Fermi writ large”

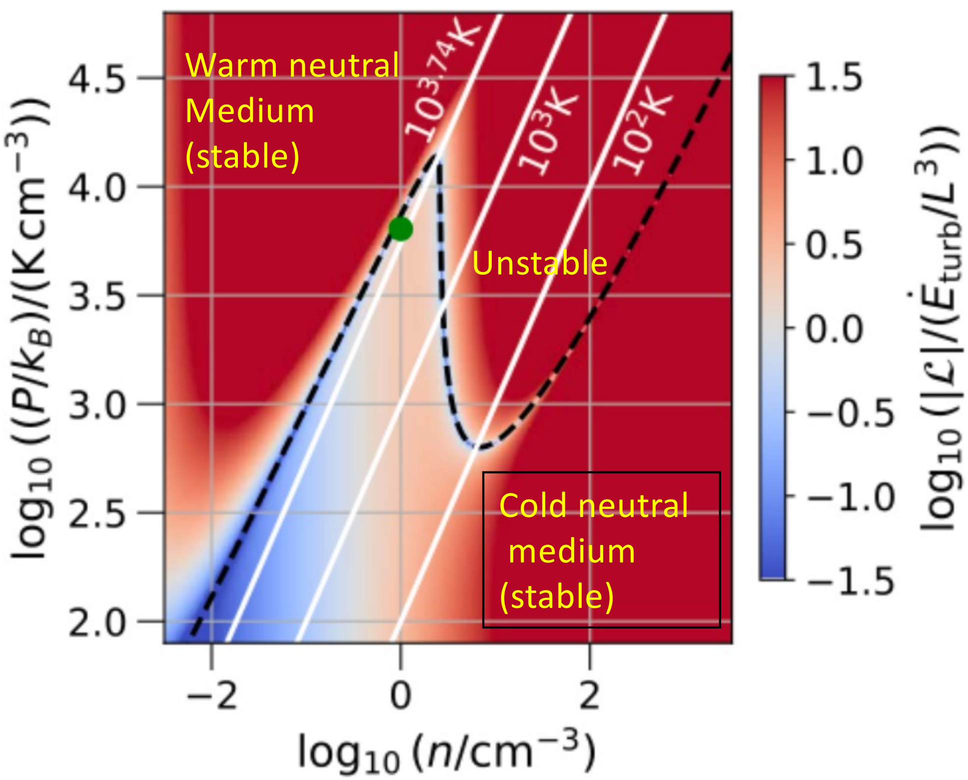
Can also be cast in the fluid picture:

$$\frac{\partial \delta P_c}{\partial t} = -\gamma_c P_c \frac{\partial \delta v}{\partial x} + \kappa_{\|} \frac{\partial^2 \delta P_c}{\partial x^2}.$$

$$\dot{E} = -\gamma_c P_c |k\delta v|^2 \frac{\kappa_{\|} k^2}{\omega^2 + \kappa_{\|}^2 k^4}.$$

Energy gain is maximized for $\omega = \kappa k^2$ (defines a critical κ; κ_c).

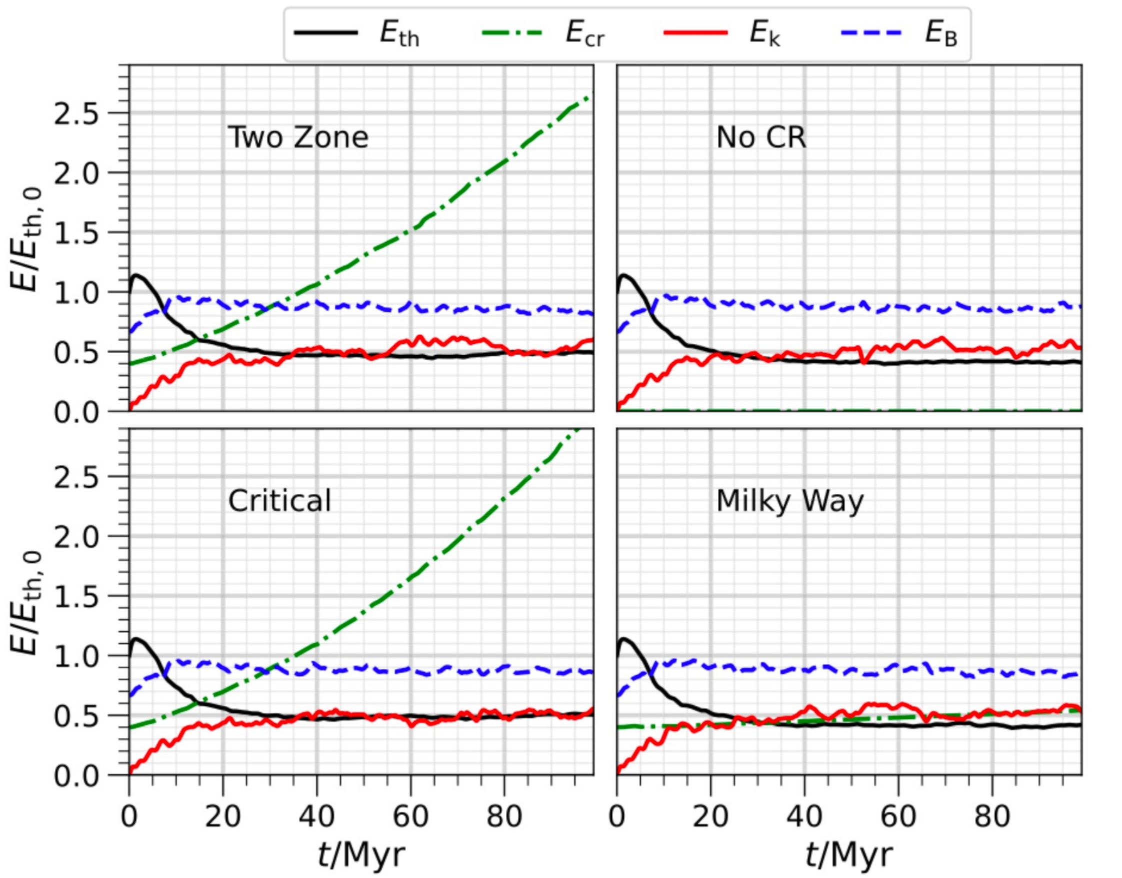
Driven Turbulence in a 100 pc^3 Cube with Heating & Cooling that Admit 2 Stable Phases



Four Cosmic Ray Transport Models:

- No cosmic rays
- Milky Way diffusivity 3 x 10^{28} cgs
- "Critical" diffusivity 5.8 x 10^{25} cgs
- Two zone diffusivity: κ_c for warm gas, κ_{MW} for cold gas.

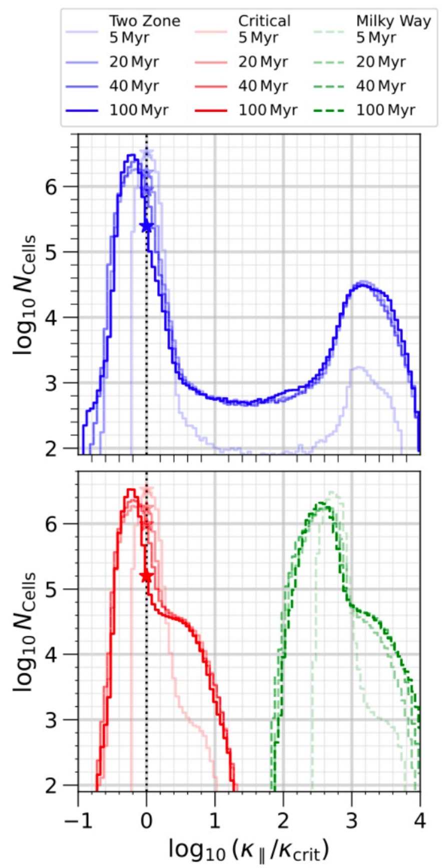
Energization by Turbulent Driving

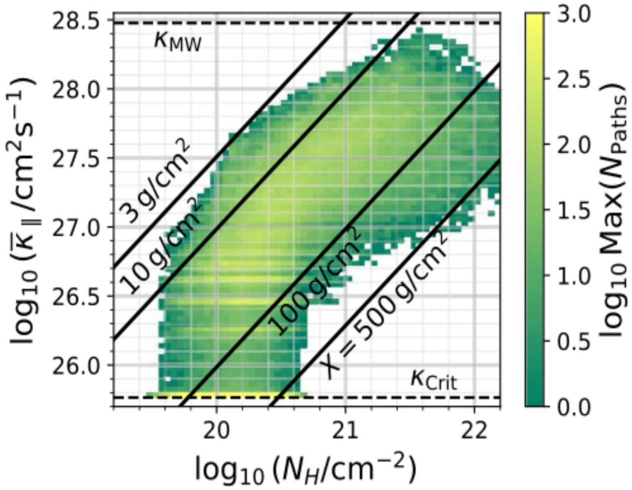


Global energy input rate is adjusted continuously to the same constant value for all 4 models.

- Only the cosmic ray energy evolution varies amongst the models.
- Without strongly coupled cosmic rays, dense gas forms by turbulent compression and energy input is balanced by radiation.
- Strongly coupled cosmic rays pressurize the gas, inhibit compression, reduce cooling, and absorb the energy injected by turbulence.

Are the Models Consistent with B/C Ratio Grammage? *Maybe Not*.





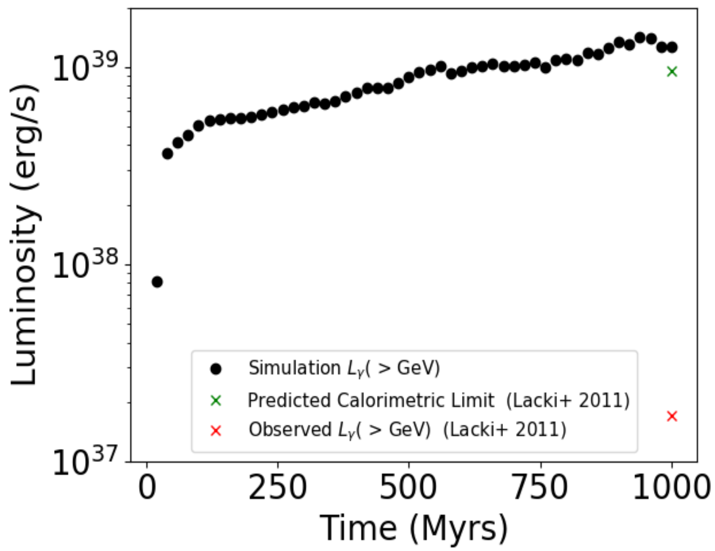
- The Milky Way histogram is closest to derived value for κ.
  - The critical value is clearly too high.
  - The two zone model has a MW-like peak, but it ‘s much lower than the critical diffucivity peak.

These trends are reflected in the “grammage” plot on the right, where each point is a global value at a specific time.

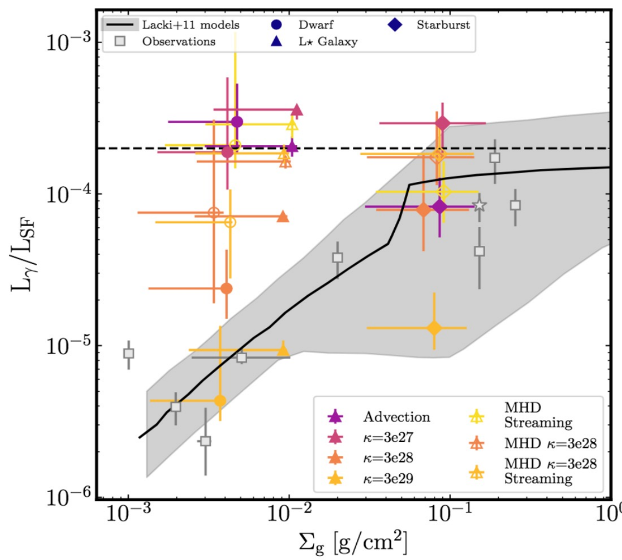
What is the Role of Turbulent Acceleration?

- We characterized it & found that radiation and thermal instability are important factors under ISM conditions.
- Unlikely to be a significant contributor to the mean Galactic flux.
- Possibly significant in the ISM regions of reduced diffusivity.
- Other systems, other galaxies?

A Lurking Problem: Can These Models Predict Gamma Ray Luminosity L_γ?

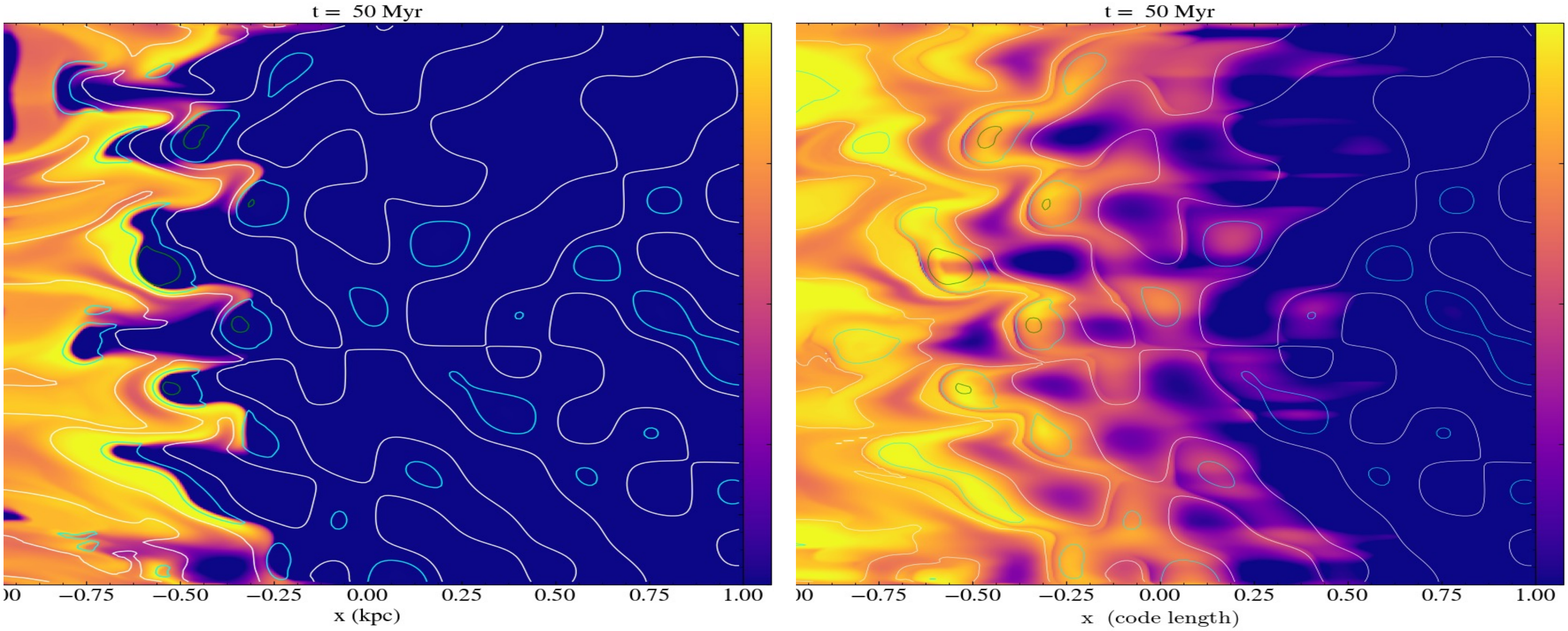


Simulation of Large Magellanic Cloud, incorporating known star formation history, from Chad Bustard, including streaming & losses



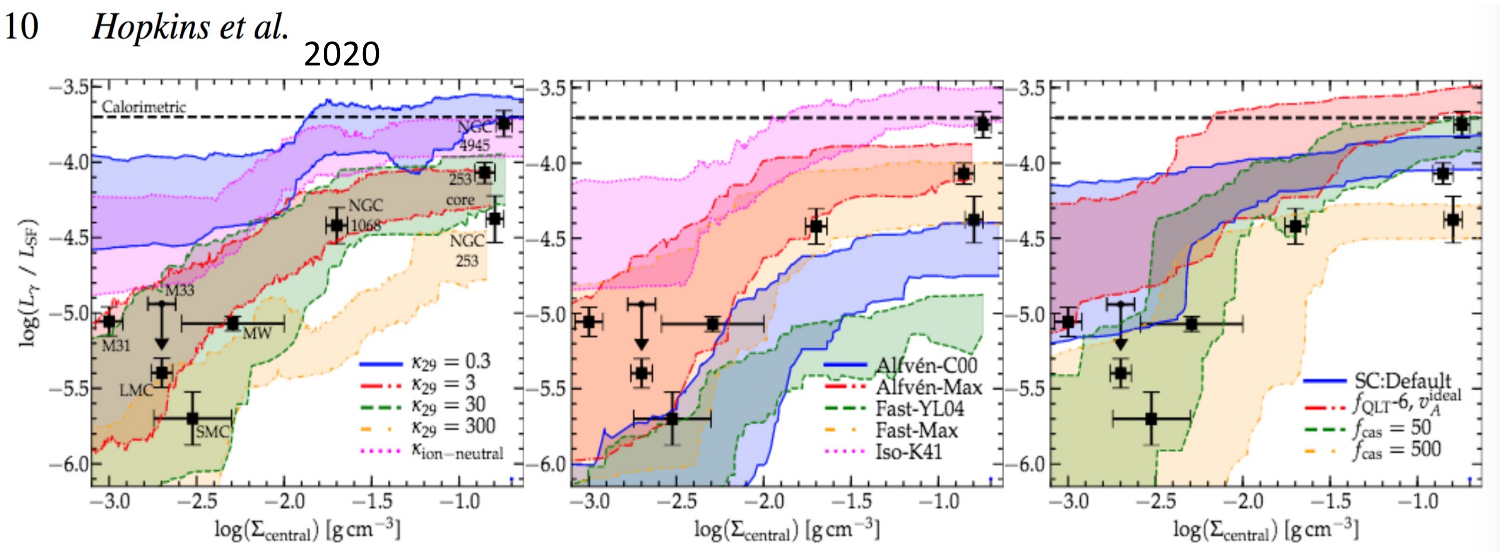
FIRE simulations with a variety of transport models, compared to FERMI detected galaxies. Chan et al. 2018

Gamma Ray Emission as a Probe of Cosmic Ray Transport



Gamma ray emissivity corresponding to the 2 propagation models without (left) & with (right) Neutrals. From Bustard et al 2020, in preparation.

Extensive Tests with FIRE



Consistent message: Models overpredict L_γ unless (a) the streaming speed is greatly boosted, or (b) the diffusivity is greatly Increased. **What is the solution?**

The Cosmic Ray-Gas Correlation in Galactic Disks and Structure Formation at Mesoscales *(Habegger & EZ 2023, Paper II almost finished).*

- Stability considerations limit the degree to which galactic disks can be supported by magnetic fields and cosmic rays.

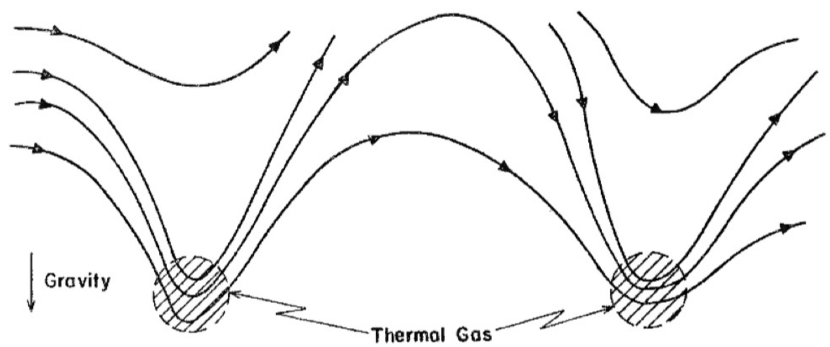
Parker's Instability: Parker 1966*

Free energy source : gravitational potential energy of gas supported above its natural scale height by magnetic fields & cosmic rays.

Energy cost: work needed to compress the gas & bend magnetic field lines.

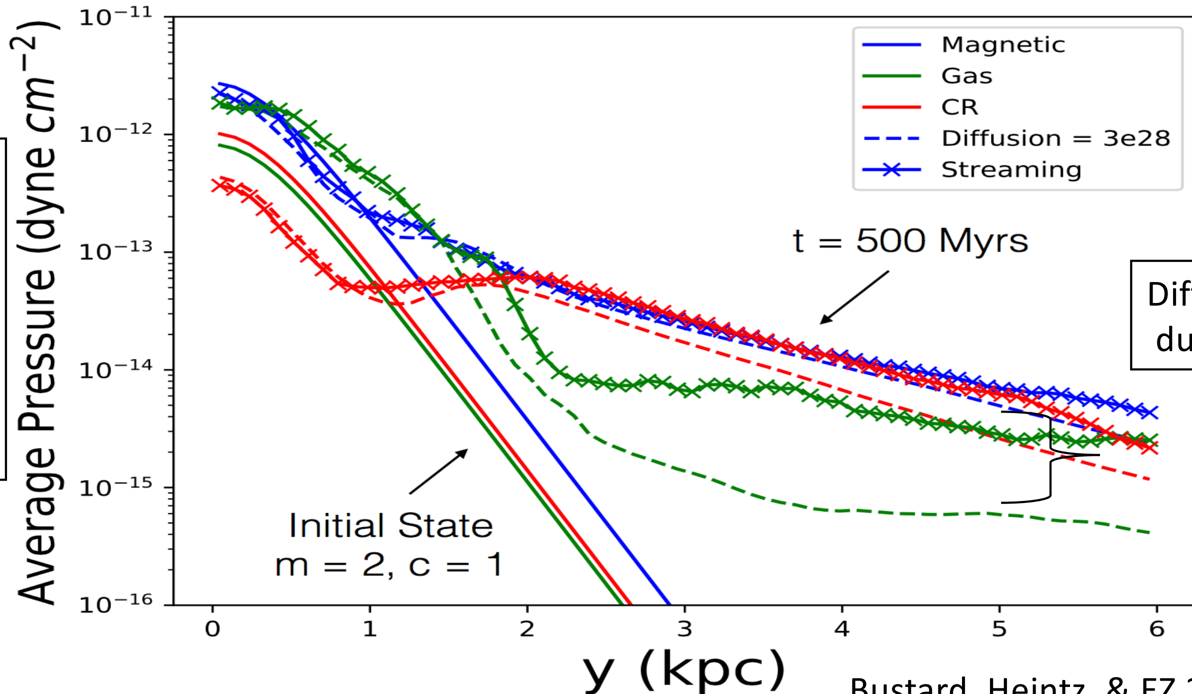
Effects: restructuring ISM, galactic dynamo, magnetic buoyancy in accretion disks.

* Streaming instability & its consequences introduced in 1969



Given Enough Time & Favorable Cosmic Ray Transport, Parker Instability Works as Claimed

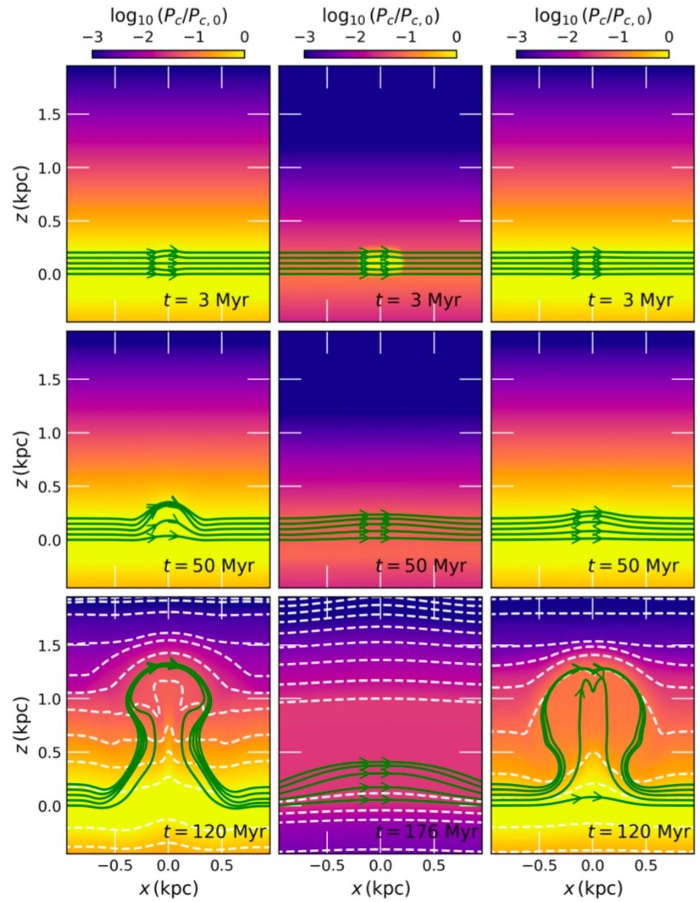
Nonthermal Pressure dominates at large heights in evolved state



Difference in gas pressure is due to cosmic ray heating.

Bustard, Heintz, & EZ 2020

Buoyancy Effects & Accelerated Timescales with Localized Injection (Habegger, EZ, Wong 2023)

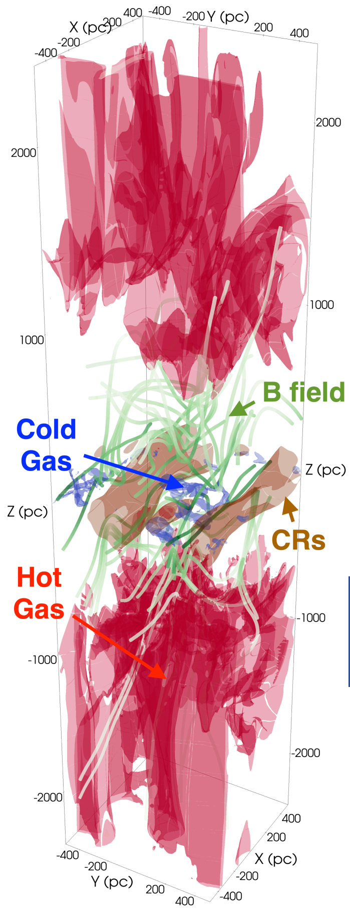


Results of instantaneous cosmic ray injection onto a magnetic flux tube (shown in green) slightly above the midplane of a 2kpc wide, 3D box of ISM (MW parameters). Cosmic ray pressure pushes gas out of the tube, which becomes buoyant, rises, and drains material even faster. *Third dimension is very important.*

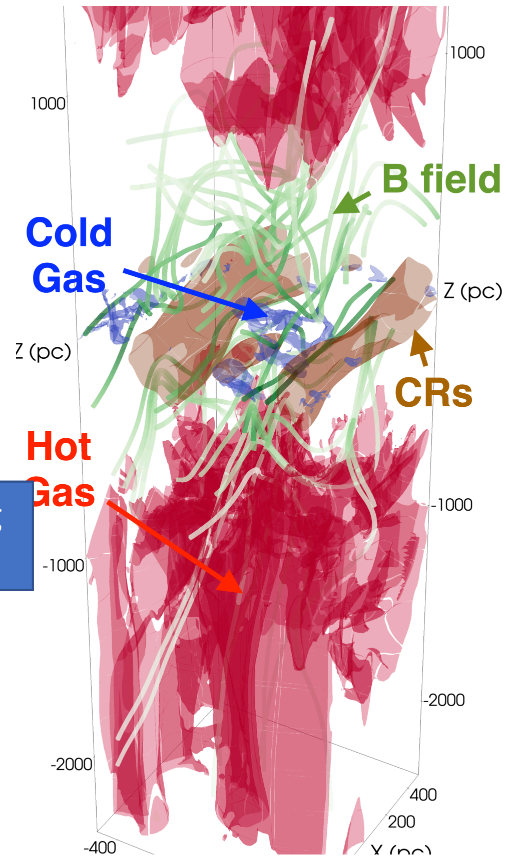
The 3 columns contrast different models of transport.

- Left: Advection
- Center: Streaming
- Right: Diffusion.

Restructuring By Multiple Injections at the Milky Way Star Formation Rate



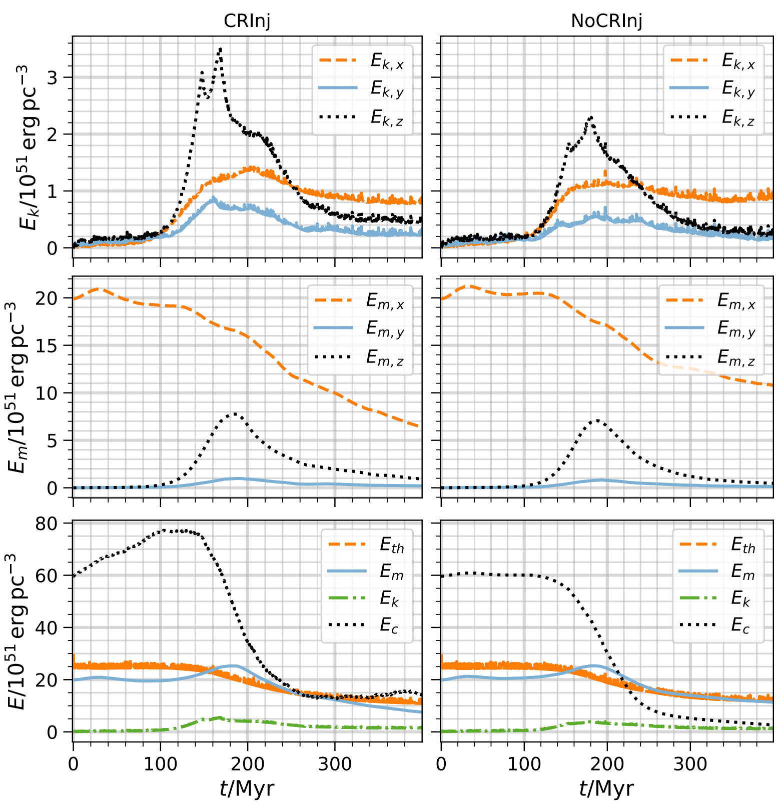
Restructuring at 180 Myr.

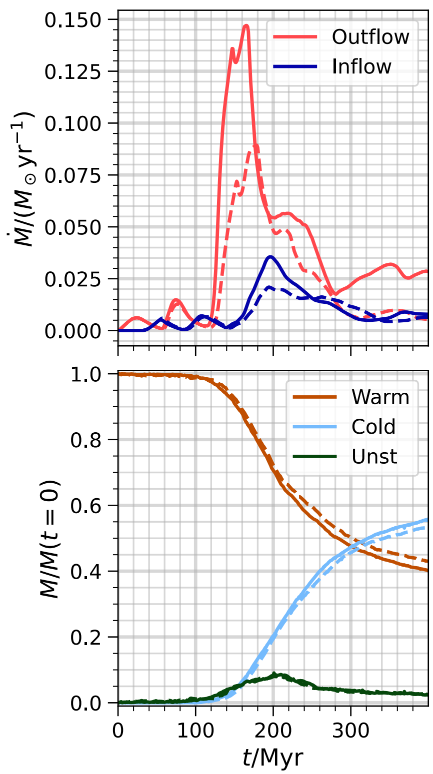


Transport is by streaming & diffusion at MW diffusivity.

- Cold gas is concentrated in a thin layer in the galactic plane.
- Magnetic field is drawn into arches with vertical legs along which cold gas streams.
- Cosmic rays and dense gas are not well correlated.

What do the Cosmic Rays Actually Do?





Compared to a model in which injected energy is thermal…

- Cosmic rays drive significant vertical flows
- Cosmic rays may be driving a wind.
- Must go beyond slab model to test this.

What We Needed for These Results

Physics

- Localized, sporadic energy injection on magnetic flux tubes.
- Heating and cooling.
- Gravity
- Both diffusion and streaming.

Computation

- 3D with high resolution
- Robust algorithm for cosmic ray transport.

Summary & Conclusions

- The mesoscales – intermediate between kinetic and global – contribute new phenomena:
  - Bottlenecks
  - Cosmic Ray heated fronts
  - Cold gas formation
  - Faster restructuring of ISM
  - Possibility of detailed cosmic ray – gas correlation modeling.
- Turbulent, distributed acceleration should be followed up but we confirm that point sources most likely dominate.
- Still need a first principles, rigorous transport theory.

Conclusions

- It's well established that cosmic rays play an important role in models of structuring galactic disks, driving galactic winds, & star formation feedback.
- Results are dependent on transport model, overpredict gamma ray luminosity, and sensitive to numerical resolution.
- Path to surmounting these difficulties: high resolution studies that include detailed gas physics & can inform subgrid prescriptions

Thank you!